CORRELATION OF DIFFERENT IMPACT CONDITIONS TO THE INJURY SEVERITY OF PEDESTRIANS IN REAL WORLD ACCIDENTS

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Paper Number 05-0352

ABSTRACT

This study aimed to investigate the correlation of different impact conditions to the injury severity and impact biomechanics of pedestrians in real world accidents, and study the tolerance level with focus on head-brain of adults and children via in-depth analysis and reconstructions of real world accidents.

For this purpose, 188 pedestrian accident cases were selected from existing accident databases. Of which 186 cases obtained from GIDAS (German In-Depth Accident Study) documented by Accident Research Unit at Medical University Hannover in Germany, and 2 cases from Sweden. For each collected case, complete information regarding pedestrian injuries, accident cars, and crash environment was registered based on hospital clinical record and police report. In order to find the correlation of injuries observed in accident with physical parameters during a collision, reconstructions of selected 8 adult- and 12 child-pedestrian cases were conducted by using pedestrian and passenger car models. The pedestrian models were generated based on the height and weight of pedestrians involved in accidents. Each car model was built up based on the corresponding accident car. The mechanical properties of the accident cars were defined based on available data from EuroNCAP tests.

The correlations of calculated injury parameters with injury outcomes registered in the accident database were determined. Influences of impact conditions and pedestrian initial moving posture on HIC value were analyzed and discussed. Furthermore, the relative importance of the factors was determined according to their effects on various injury parameters. The difference of injury distribution and dynamic responses of pedestrians at various body sizes for adult and child were analyzed, which would provide background knowledge to develop safety counter-measures and protection devices.

INTRODUCTION

The pedestrians are the most vulnerable road users who exposure a high risk in road traffic collisions with motor vehicles. Each year, about 1.2 million people are killed in road vehicle traffic worldwide, of which the pedestrians account for a large part of the traffic fatalities, especially in low- and middle-income countries. In high-income countries, car occupants account for a large majority of road users and the majority of road traffic deaths. Nevertheless, even there, pedestrians, cyclists and moped and motorcycle riders have a much higher risk of death per kilometer traveled [1].

The studies in Europe [2-4] indicated that the passenger cars are most commonly involved in pedestrian accidents. Figure 1 shows a distribution of vehicle type in pedestrian accidents which based on accident data from Swedish national accident database STRADA.

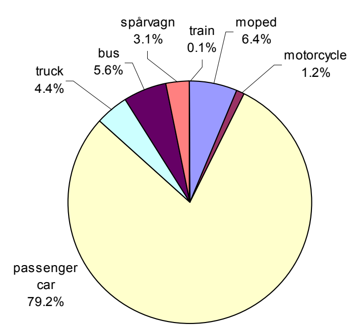


Figure 1. Involved vehicle types in pedestrian accidents based on Swedish national accident database STRADA (1999-2004).

During the past three decades significant reductions in pedestrian fatalities have been achieved in Europe [5] and the United States [6]. This tendency is mainly due to improved traffic planning in built-up areas. Other safety program such as appropriate speed limits, drink driving control, education of young people could also contribute to the reduction of casualties. So far, there is not any statistical study to prove that injury reduction is caused by changes of car-front shape, but the findings from studies suggest that a potential benefit can be obtained from improvement of new vehicle designs which meet the EEVC requirements.

A study on pedestrian accidents is presented in this paper with focus on detailed individual case analysis via accident reconstruction using the mathematical models. The objective of the study is to determine the correlations of impact conditions and dynamic responses with the injuries and injury severity of pedestrians from accident. The results were analyzed and discussed in terms of data collection, estimating vehicle impact speeds, pedestrian moving speeds and initial posture, secondary ground impact, as well as impact biomechanics.

METHOD AND MATERIALS

Accident cases were selected from the accident database GIDAS (German In-Depth Accident Study) documented by Accident Research Unit at Medical University Hannover [7, 8]. In the district of Hannover a representative sampling of accidents is carried out by order of the German Government (Federal Highway Research Institute BAST) in co-operation with the car manufacturers. A general statistics analysis was carried out with the collected sample cases. Reconstructions were conducted using selected cases from the whole samples. The results from accident reconstructions were analyzed and discussed.

Selection of Accident Cases

For the purpose mentioned above, 188 pedestrian accident cases were selected from Hannover Medical University, of which 117 adult- and 69 child-pedestrian accident cases, and 2 cases from Sweden. For each collected case, complete information regarding pedestrian injuries (AIS1+), damage of accident cars, and crash environment was registered based on hospital clinical record and police report. The anthropometric data of pedestrian such as age, gender, height, and weight were also documented in the hospital. Accident witnesses were investigated to obtain the accident information such as pedestrian posture, impact direction etc.

The passenger cars involved in the accidents were recorded with detailed information about car makers, model, registration year, estimated impact speed. The selected cases were limited with accident car introduced to the market after 1990. The deformation pattern, contact points on the car and characteristics of special traces on the road and on the car were measured and documented in a 3D coordinate system with reference to longitudinal central line of vehicle. Pictures of impact location are documented and could be used for analysis. The final positions of the pedestrian and car were also recorded. Thus these accidents reflect the most up to date pedestrian accident characters.

Selection of Accident Cases for Reconstruction

Further screening the collected cases was carried out for reconstructions that request very detailed accident data in pre-crash, crash, and post crash phases. The requested data are summarized in Table 1. It is necessary to mention here that some information for accident reconstruction is not possible to acquire from field investigation, such as the vehicle front stiffness, and kinematics of the pedestrian collision.

In the present study, 8 adult cases and 12 child cases were selected for accident reconstructions. Two examples are described in following section.

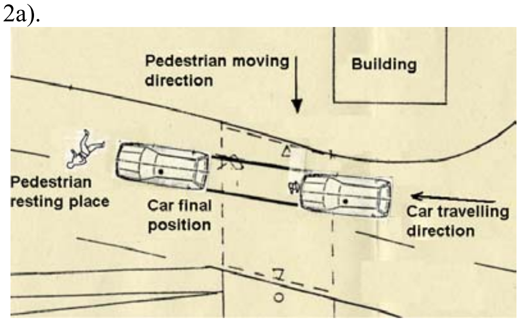
Table 1. Summary of accident data collection for reconstruction in case 1

	Pre-crash	Crash	Post crash
Vehicle	- Travel speed - Pre-crash braking - Driver maneuver	- Impact speed - Contact point	- Maker, model, year, weight - Damage (dents, scratch)
Pedestrian	- Initial posture - Moving speed - Orientation	Grass Kinematics Wrap around distance Throw distance - Landing point - Sliding distance - Resting point Ground impact mode - Body contact	- Gender, Age, Height, Weight Injuries - Injury patterns - Injury distribution - Severity - Cause of injury
Road and Environment	- Road type - Road surface - Weather condition	Ground impact	- Skid mark and other traces

Example Case 1: Adult Pedestrian Accident

Pre-crash

A passenger car-to-pedestrian accident happened in a residential area in Hannover, Germany (Figure 2a).



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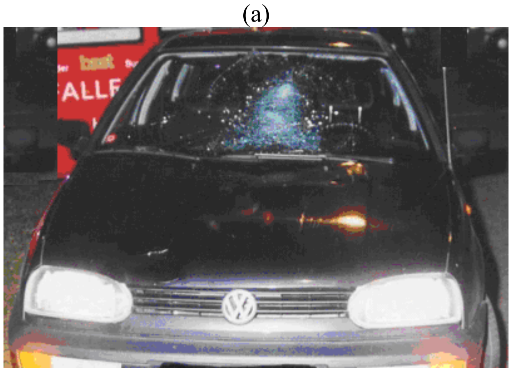

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Figure 2. (a) Scheme of accident scene, (b) the location of head impact on windscreen and pelvis impact on hood top.

The accident car is a VW Golf III 1993 model. The car was traveling over a cross in which corner standing a building. A 70-year-old male walked fast behind the building to cross the street. Because of the building, the driver could not see the man in advance. After the driver saw the man, he braked hardly but still hit the man. The impact speed was about 43 km/h.

Crash

The car hit the left leg by the right side of the bumper. The head impacted against the windscreen. The scratches and damages of the vehicle are shown in Figure 2b. The man was thrown away for about 11 m.

Post crash data

The man sustained laceration wound at the head, oedema of the brain, concussion and fracture at the left tibia.

Example Case 2: Child Pedestrian Accident

Pre-crash

A passenger car-to-child pedestrian accident occurred in a resident area in Hannover, Germany.

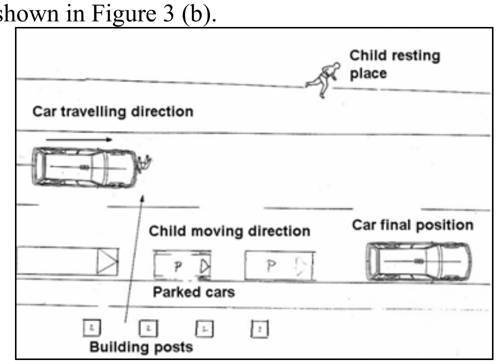
The accident car is an OPEL Omega Combi 1994 model. The car was traveling on a street where several vehicles were parking along right side (Figure 3a). A 4-year-old boy walked fast to cross the street. Because of the parked car, the driver could not see the boy in advance. After the driver saw the boy, he braked hardly but still hit the boy. The impact speed was about 25 km/h.

Crash

The car hit the child by the left front part. The boy was thrown away and the throw distance was about 6 m.

Post crash data

The child sustained AIS 2 head injury, AIS 1 lower extremity injury. On the vehicle, scraps on the bumper and dents on the hood were found as shown in Figure 3 (b).



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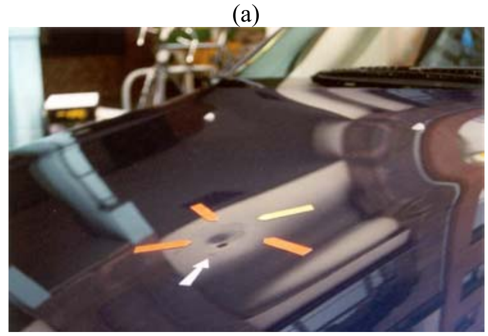

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Figure 3. (a) Scheme of accident scene, (b) Scraps and dent on the accident car

Accident Reconstructions

The selected accident cases are reconstructed using pedestrian models and passenger car models. The reconstructions were carried out by using MADYMO program.

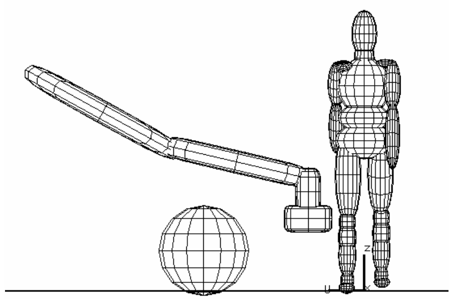
The Set-up of Reconstruction Models

The anthropometric data of the pedestrian models used in the reconstructions are summarized in Table A1 (Appendix), which based on the height and weight of pedestrians involved in accidents.

The pedestrian models were generated by GEBOD code in MADYMO program for both adults and children. The characteristics of the adult models was defined based on a validated human body model [9, 10]. The characteristics of child models were scaled from the validated adult pedestrian model.

The car models were built up based on the corresponding accident car. The geometry of the car models was obtained from the drawings of the production cars that had the same make, model and series as those involved in the accidents. The mechanical properties of the car models were defined in terms of stiffness properties acquired from Euro NCAP sub-system tests.

The impact speeds of the cars and the pedestrian moving speeds were estimated based on the accident data, considering the car braking skid marks on the road surface and the pedestrian moving postures before the impact. The friction coefficient between the wheels and road surface was defined according to road surface conditions. The diving angle of emergency braking and steering effect were also simulated. The Figures 4a and 4b show the reconstruction models for example adult and child accidents.



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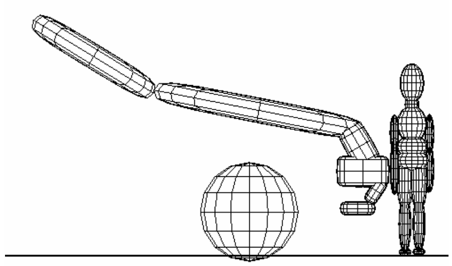

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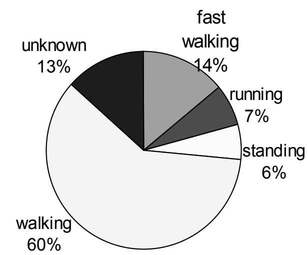
Figure 4. Simulations of (a) adult pedestrian accident, (b) child pedestrian accident.

The kinematics was simulated in reconstructions of the selected accident cases. The injury parameters in head, chest, pelvis and lower extremities were calculated to evaluate the injury severities from the accidents. The correlations of the output parameters from simulations with the injuries described in medical and accident report were analyzed. The threshold of brain injury parameters, such as HIC was discussed based on reconstruction results.

RESULTS

General Statistic Analysis

The initial posture at the moment of impact was determined at running, fast walking, walking or standing. Figure 5 shows that half of children were running but only 2% children were standing when they were hit by the vehicle. This is remarkable comparing to the situation of adult pedestrians (7% running). The accident data also showed that 82% adults and 87% children were impacted from the lateral direction.



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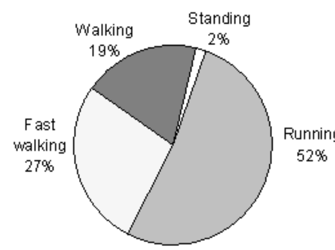

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Figure 5. Pedestrian moving posture at the moment of impact: (a) adults, and (b) child.

The injury distribution of pedestrian is shown in Table 2. It was observed that the head and the lower extremities were the two most frequently injured body parts during the accidents for both adults and children, but adult lower extremities are more frequently injured than children. For AIS 2+ injuries, head injuries accounted for 30.9% for adults and 56.4% for children, respectively.

Table 2. Injury distribution by body regions

Body	AIS 2+		All injuries	
	Adult	Child	Adult	Child
Head	30.9%	56.4%	25.9%	33.1%
Neck	4.3%	0.0%	5.0%	1.8%
Thorax	12.8%	7.7%	12.0%	5.5%
U-Limbs	7.4%	12.8%	16.6%	20.9%
Abdomen	1.1%	0.0%	1.9%	3.0%
Pelvis	5.3%	0.0%	6.2%	8.6%
L-Limbs	38.3%	23.1%	32.4%	27.0%

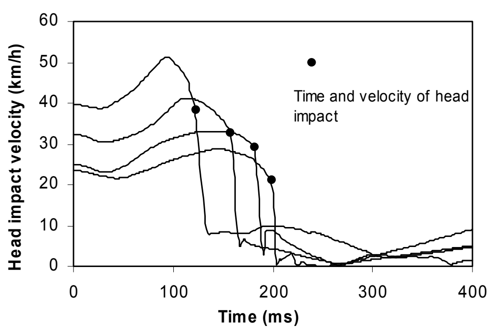
Reconstrustion Analysis

Overall kinematics of pedestrian

The contact location of head on the vehicle could be defined by the wrap-around distance (WAD) along the car-front surface. Results from accident reconstructions show that the WAD is influenced by the pedestrian height and impact speed. Table A2 (Appendix) shows the overall kinematics of pedestrians from reconstructions. The wrap around distance was close to the information collected by police.

Head impact conditions

The head impact conditions to the car front were determined for each case in terms of head resultant impact velocity relative to the car, head impact angle relative to the horizontal, head impact location, as well as timing of head impact.



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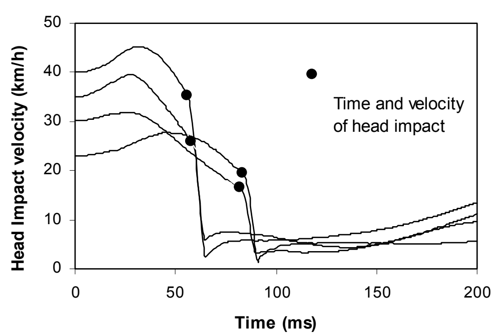

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Figure 6. The time history of head resultant velocity relative to car front: (a) adult, (b) child.

Figure 6a and 6b illustrate the time history of the head resultant velocities for 4 adults with the height of around 170 cm and 4 children with the same height of 120 cm. The head impact timing varies from 123 ms to 199 ms for the adults, and from 56 ms to 83 ms for children. The results indicated that the head impact timing varied in a wide range due to vehicle speed and size of the pedestrians.

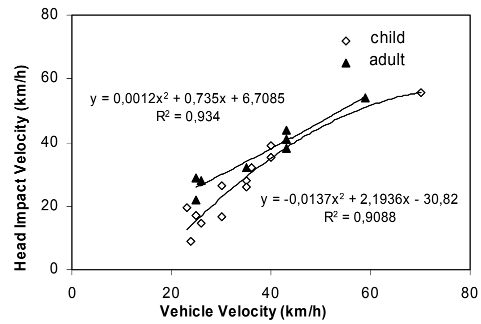

Figure 7. Relationship between head impact speed and vehicle speed

The head impact speed appears to be proportional to vehicle impact speed as shown in Figure 7. Normally, the child head impact speed is lower than the vehicle travel speed at the moment of impact.

The head impact angle could be greatly influenced by several factors such as the pedestrian height, hood edge height, hood angle and impact speed. The individual contribution of each factor to the head impact angle should be investigated using more detailed parameter studies. Figure 8 shows the relationship between head impact angle and vehicle velocity. The results showed that the head impact angle usually decreases with the increasing of vehicle impact speed for both adult and child.

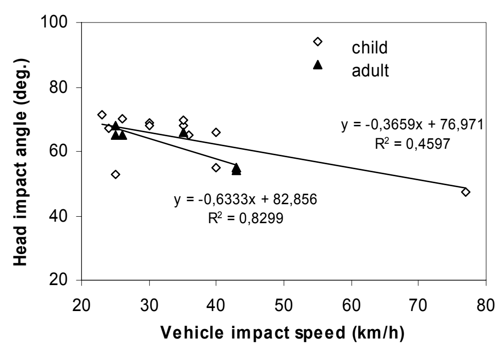

Figure 8. Relationship between the vehicle impact speed and head impact angle

Calculated injury parameters

The head injury risks were evaluated by calculating HIC as shown in Table A3 (Appendix). The relative importance of ground and vehicle in causing the head injury is investigated in terms of HIC ratio β which is defined as follows:

$$\beta_{HIC} = \frac{HIC_{car-impact}}{HIC_{ground-impact}} \qquad [1]$$

Table A3 shows that during the second impact, it could be the head or other body parts that first landing on the ground. If the head first landing on the ground, it has a high injury risk of the head caused by ground.

The relationship between head injury severity and vehicle impact speed is shown in Figure 9. A nonlinear correlation is achieved by a second-order polynomial curve.

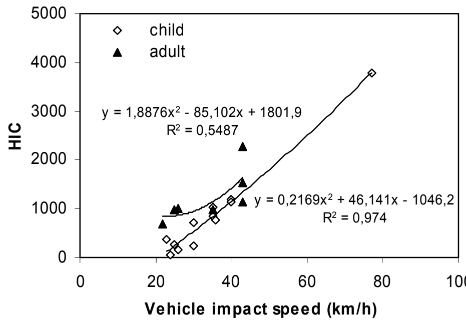

Figure 9. Correlation of vehicle impact speed and HIC

Throwing Distance

Figure 10 shows the calculated pedestrian throwing distances in accident reconstructions, which are comparable with the throwing distances registered in police report. It appears that the child throwing distances are greater than that of adult at the same impact speed.

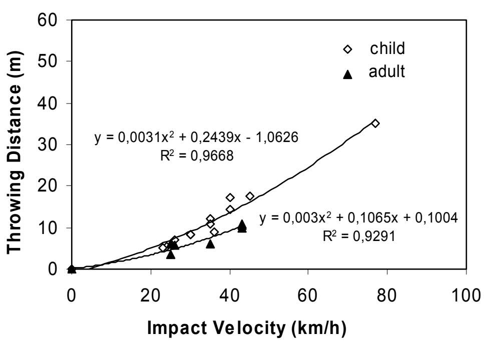

Figure 10. Throwing distance

DISCUSSION

In this study efforts have been made to find the correlation of the calculated biomechanical responses of pedestrian body segments with the corresponding injuries observed in accidents. The reliability of the findings from accident reconstructions is dependent on quality of data sources, including information about three aspects: vehicles, pedestrians, and road traffic environment.

Data sources and the basic variables

The accident data used in these studies were collected from hospital clinical record and police report, which contributed to form national databases. This study was carried out based on the databases for acquisition of detailed information about causation and occurrence of accidents, injury patterns, causation and distribution of the injuries. The collected information forms firm background for in-depth study on impact biomechnics and injury correlations of pedestrians in vehicle collisions.

Estimating vehicle impact speeds

The vehicle impact speed is one of the most important issues to investigate the pedestrian impact responses and injury biomechanics. There are various approaches to estimate the vehicle speed at the moment of the collision. In the present study the following techniques were used to estimate the vehicle impact speeds based on available accident data.

Vehicle speed based on skid marks

Calculation of vehicle speed by using skid marks is the most common way in pedestrian collision analysis, in the case of accident vehicle skidded after an emergency braking. The length s of the skid marks can be measured in field investigations. The possible car impact speeds V_i are calculated using equation as follows:

$$V_i = \sqrt{2g\mu s} \qquad [2]$$

It is necessary to point out that there could be some difference of the calculated speed from the speed in real world accident due to effect of pedestrian mass and road surface conditions.

Vehicle speed based on pedestrian throw distance

The skid marks are not always available in accident field. One of the reasons is due to the increasing use of Anti-lock Brake Systems, skid marks are less common. The pedestrian's total throw distance is another indicator of the speed of the vehicle at impact. Estimating vehicle speed by pedestrian throw distance is thus becoming more important in accident investigations. The vehicle impact speed can be estimated by simulation of the vehicle and pedestrian motions [4].

Pedestrian initial posture and moving speeds

In the real world vehicle-pedestrian accidents the initial posture of a pedestrian at an impact is varied in different motion attitude. Therefore an appropriate initial position should be investigated and defined for reconstruction of the pedestrian accidents. According to present study, the child initial posture in an accident is quite different from that of an adult.

The majority 98% of the child pedestrians are in motion during impact, either walking or running. This indicated a remarkable difference from study on initial posture of pedestrians in all age group, of which 79% in motion [11].

The impact responses and injury outcomes are significantly affected by the initial postures and the orientation of body segments. It was proposed to take into account the leg orientation for the moving posture. During the pedestrian impact the kinematics and dynamic loading of pedestrian are not the same if you have the left leg forward or the right leg forward.

The moving speed is another important variable to define in accident reconstruction. The child normal crossing speeds were established as 1.5 m/second to 2 m /second, which are recommended to be used in present study.

Secondary ground impact

In reconstruction results the HIC values were calculated in both first contact with car and second contact with road surface. It is usual that the HIC value in contact with car front is lager than that in second ground impact without head landing ground first. The reverse is the case for the second ground impact with head contact ground first. It indicated that the contact modes in secondary ground impact are complicated, which could be dependent to the vehicle front shape, impact velocity, and body size.

Impact biomechanics

It was found that the injury distribution of pedestrians varies with the body size. In general children exposure higher risk for head injuries, and adults for lower extremities.

The HIC is an important measurement of the head injury. The results show a good correlation between calculated injury parameters and the head injury severities in the accidents. However, more accident cases are needed to establish a tolerance level and a correlation of head injury risk with HIC value.

CONCLUSIONS

In car-pedestrian accidents, the pedestrians are often struck from the side by the front structure of a vehicle when crossing a street. In this study it was found that the pedestrians were hit from the side for 82% of adult cases and 87% of the child cases

It was found that the child head injuries account for 56.4% of total child pedestrian injuries, adult head injuries for 30.9% of total adult pedestrian injuries.

The head impact conditions such as impact velocity, impact timing and angle, wrap around distance are mainly dependent on the car front shapes, impact speed and size of child pedestrian.

The head injuries caused by car front structures were usually much severe than caused by the secondary ground impact.

The impact velocity and car front structures have a significant influence on the kinematics and injury severity of child pedestrian head. By limiting the vehicle speed and improving car front design, the head injury severity of child pedestrian could be reduced.

The dynamic responses and injury parameters from accident reconstructions would provide complement knowledge to develop safety countermeasures and protection devices.

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APPENDIX

Table A1a. Anthropometric data of adults

Case No.	1	2	3	4	5	6	7	8
Age	62	24	81	49	50	70	28	84
Height(cm)	170	155	153	168	180	175	170	150
Weight (kg)	90	50	45	70	87	85	69	55

Table A1b. Anthropometric data of children

Case No.	1	2	3	4	5	6	7	8	9	10	11	12
Age	7	9	12	4	7	6	6	6	5	6	4	8
Height(cm)	123	130	120	110	120	113	120	115	120	126	110	128
Weight (kg)	25	30.7	45	18	31	22	18	12	25	31	17	25

Table A2a. Correlation of WAD distance with adult pedestrian height

Case No.	1	2	3	4	5	6	7	8
Height (cm)	170	155	153	168	180	175	170	150
WAD_R (cm)	173	146	149	188	207	191	172	163
WAD_R/Height	1.01	0.94	0.97	1.12	1.15	1.09	1.01	1.09

Table A2b. Correlation of WAD distance with child pedestrian height

Case No.	1	2	3	4	5	6	7	8	9	10	11	12
Height (cm)	123	130	120	110	120	113	120	115	120	126	110	128
WAD_R (cm)	131	136	100	97	109	103	104	112	111	119	93	118
WAD_R/Height	1.06	1.05	0.83	0.88	0.91	0.91	0.87	0.97	0.93	0.94	0.85	0.92

Table A3a. Calculated injury parameters from adult accident reconstructions

Case No.	1	2	3	4	5	6	7	8
Vehicle speed (km/h)	25	43	26	35	59	43	25	43
HICcar-impact	682	1138	984	980	1397	2278	984	1534
HIC ratio	14.8	0.8	6.4	0.5	2.4	3.9	0.8	0.7
Landing body part	Arm	Head	Arm	Head	Foot	Foot	Foot	Arm
Head injury (MAIS)	2	2	2	2	3	3	1	2

Table A3b. Calculated injury parameters from child accident reconstructions

Case No.	1	2	3	4	5	6	7	8	9	10	11	12
Vehicle speed (km/h)	40	36	23	35	30	24	35	77	40	26	25	30
HICcar-impact	1147	764	367	1041	227	58	851	3788	1182	166	263	725
HIC ratio	1.23	1.10	1.11	1.03	0.51	0.10	1.08	0.77	1.14	0.89	0.33	0.99
Landing body part	Foot	Foot	Head	Foot	Foot	Head	Foot	Head	Foot	Head	Head	Head
Head injury (MAIS)	5	5	1	2	0	1	1	6	5	0	2	1